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A framework for designing multi-objective landscapes for conservation☆

Alienor L.M. Chauvenet[a,*,1], Anna R. Renwick[b,1], Hugh P. Possingham[b], Vanessa M. Adams[c], Jennifer McGowan[b], Vesna Gagić[d,e], Nancy A. Schellhorn[d]

[a] School of Environment and Science, Griffith University, Southport, Queensland, 4222, Australia
[b] Centre for Biodiversity and Conservation Science, University of Queensland, Brisbane, Queensland, 4072, Australia
[c] Discipline of Geography and Spatial Sciences, University of Tasmania, Hobart, Tasmania, 7000, Australia
[d] CSIRO, Ecoscience Precinct, GPO Box 2583, Brisbane, Queensland, 4001, Australia
[e] Horticulture and Forestry Science, Department of Primary Industries, EcoSciences Precinct, Dutton Park, Queensland, 4102, Australia

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ABSTRACT

Designing landscapes to accommodate both humans and nature poses huge challenges but is increasingly recognised as an essential component of conservation and land management. The land-sparing land-sharing approach has been proposed as a tool to address this challenge. However, its focus on an ideal landscape configuration leaves a gap on what step-wise management decisions are needed to transform the existing landscape to reach that ideal endpoint. We provide a new conceptual framework amenable to the application of structured decision-making to identify the step-wise pathways between the present landscape and a desired landscape given a defined objective and fixed budget. The model can be parameterised for specific systems using information about: the current state of the landscape, the rates of change between landscape states, and the cost and effectiveness of taking actions. To demonstrate this, we apply it to three different landscape types and find that investment into one of three management actions (varying degrees of management and restoration) can move the system towards more biodiversity or more managed land depending on the objectives of the stakeholders. The dynamic and flexible nature of the framework makes it useful for decision-making in a land sparing land sharing context.

1. Introduction

Land degradation and clearing is a major cause of biodiversity loss and decreased ecosystem services, and ultimately poorer land production systems (Gisladottir and Stocking, 2005). Conserving biodiversity while meeting human needs from ecological systems (such as food production) requires trade-offs. This interplay between the biodiversity crisis and global food security is recognised internationally with nations committing to halt further extinction of species and safeguard biodiversity (Convention Biological Diversity, 2022) and to sustainable development to meet the world's human population needs (The World Bank Group SDG Fund, 2015).

Expanding the global protected area system – for example as called upon in Target 3 of the Kunming-Montreal Global Biodiversity Framework (GBF; Convention Biological Diversity, 2022)– is one key intervention to address land degradation. However, meeting the broader goals of the GBF requires other interventions, such as restoration and management at landscape scale. Thus land-use planning should consider not just protecting and conserving intact land, but also restoring degraded ecosystems towards a more desirable state, both for people and nature (Adams et al., 2019; Chauvenet et al., 2020; Kuempel et al., 2020; Mappin et al., 2019). However, requirements to have sufficient areas to support human needs (i.e. agriculture production, forestry, urban areas) can make achieving the needed amount of intact land for conservation outcomes challenging (Mcdonald et al., 2008; Niemela et al., 2005; Polasky et al., 2008; Tanentzap et al., 2015).

Determining the design of landscapes to accommodate both nature and human land use has become a hot topic in the conservation world; indeed regional planning is Target 1 of the CBD (e.g. Adams et al., 2023; Feniuk et al., 2019; Geschke et al., 2018; Goulart et al., 2016; Stark et al., 2021). This is of no surprise given the rapid increase in human population size (Cincotta et al., 2000) and inevitable encroachment into areas

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* Corresponding author at: School of Environment and Science, Griffith University, Parklands Drive, Southport, QLD, 4222, Australia.
E-mail address: a.chauvenet@griffith.edu.au (A.L.M. Chauvenet).

[1] Denotes shared first authorship.

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once solely reserved for nature. Land sharing or land sparing is one conceptual approach to thinking about balancing the needs of nature and humans. It emerged from the Borlaug hypothesis that claimed that the Green Revolution of intensification of agriculture had 'spared' several hundred millions of hectares of land that would have been converted into agriculture (Phalan, 2018). It was further developed by Green et al. (2005) and Balmford and Bond (2005), primarily to determine the optimal strategy for conserving species while delivering a fixed regional food production target in agricultural landscapes.

Land sparing and land sharing are the two extremes of a land configuration continuum (Geschke et al., 2018). On one hand, land sparing involves segregating the landscape by intensifying agricultural production (Finch et al., 2019; Finch et al., 2020), logging (Montejo-Kovacevich et al., 2018) and other conversion (Geschke et al., 2018), while leaving the remaining land intact for nature. The expectation is that high intensity of activity means high yield, which reduces the area required to meet human demands (Phalan et al., 2011). On the other hand, land sharing involves integrating agriculture (or other conversion activities) and biodiversity preservation within the same space, through the use of less intensive production methods over a larger area to meet the same production levels (Phalan et al., 2011). The land sparing land sharing framework has been used to design cities and plantation landscapes, livestock production, and fisheries production (e.g. Edwards et al., 2014; Law et al., 2017; Lin and Fuller, 2013; McGowan et al., 2018) as well as more traditional agricultural landscape. The framework, which is often perceived as a dichotomy, and thus too simplistic, has caused quite a divide in the ecological sector with strong advocates for and against each approach (Kremen, 2015).

Empirical evidence shows that depending on the ecological communities considered for conservation actions, either land sparing, or an intermediate level of sharing and sparing at the landscape level, perform best for both agricultural yield and biodiversity benefits (e.g. urban birds; Geschke et al., 2018; butterfly communities; Montejo-Kovacevich et al., 2018). In particular, the three compartment sparing approach (3C approach; Feniuk et al., 2019) where some of the land is spared for high yield production, and the rest is split between low yield production and no yield nature, has showed promising results to meet human and biodiversity needs (Finch et al., 2019; Finch et al., 2020). One key aspect of this approach, however, is the focus on a final optimal landscape. While compelling, the evidence that supports sparing or a modified sparing approach is derived from comparative studies of sites that already have different configurations. There remains the question of how do we move from the current landscape to the ideal landscape for production and biodiversity? Answering this question requires understanding the pathways to change a system over time in addition to agreeing upon an end destination (either through optimization or shared articulation of goals). Such adaptive planning and management, in which incremental changes are implemented and tracked to achieve a final desired goal, have been discussed in single action systems such as expanding a protected area estate (Adams et al., 2021; Boothroyd et al., 2023), but to our knowledge these have not been extended to complex multi-action multi-year contexts. In their current format, frameworks such as land sharing land sparing, don't provide the needed decision support for managers to develop such and implement such management pathways for incremental changes across multiple actions and land uses to move the system towards a more desirable state.

To address this need, we propose a new conceptual approach to landscape design grounded in a system model for landscape dynamics and structured decision-making. Rather than focusing on a utopian or optimal end-point landscape, which could be anywhere on the land sparing land sharing continuum, our approach helps decision-makers invest in various management actions towards a preferred landscape. This reflects a more realistic view of plan implementation - incremental system changes towards a preferred end point (Pressey et al., 2013). Our framework can be used to make management decisions that balance outcomes against multiple (potentially competing) goals, for example the conservation of species, ecosystem services, and production. To demonstrate the framework's utility, we apply it to three different landscape types: urban, forestry and agriculture.

2. Modelling framework

Our framework is based on a generalizable system model that can be used to better understand and plan the conservation and management actions needed to create a pathway towards a desirable landscape, wherever it is on the land sparing land sharing continuum. The model helps us explicitly define the management options that are possible for a system as well as the trade-offs between decisions. By design the model is sufficiently simple that a decision maker should be able to populate the key variables based on readily observable data; the model accounts for the current state of the system (e.g. how much land is protected and converted), the rates of change between the different states caused by either the anthropogenic threats that drive conversion (e.g. urbanisation) or as the result of conservation actions (e.g. restoration), and the cost and benefits of taking actions. The best course of action at the time will be dictated by the current state of the system (i.e. proportion of land protected or converted), the overall objective for the landscape and how benefits of actions are measured.

We note that achieving a desired future system state will typically occur over a medium to long-term (>20 years). Thus, incremental short-term management actions will have to be planned and implemented sequentially. The system model we present here can be used for decision making support, such as exploring possible sequential steps to optimal end points, visualizing complete solution spaces to identify preferred pathways, or integrated into opimitisations using benefit functions that incorporate the benefits associated with different system states, for example food production on modified or converted lands, and biodiversity on modified or intact lands. Thus, in its simplest use case, this framework would support a decision maker or stakeholder group by allowing them to quantify the current state and to visualize the complete solution space for possible actions and outcomes. In doing so they'd be able to then map a series of incremental actions within a structured adaptive planning setting to achieve their desired long-term end state. In more complicated settings a decision maker could instead use system model alongside explicit (multi) objective functions to optimize for stepwise changes, e.g. with stochastic dynamic programming (Giakoumi et al., 2025; Martin et al., 2009).

3. System model description

We draw from a conceptual model of landscape systems and the types of land management interventions available as presented by Kuempel et al. (2020). Kuempel et al. (2020) conceptualises land and seascape as a set of 6 distinct states or uses: converted habitat for multiple use (C), unprotected intact habitat (U), unprotected degraded habitat (Ud), protected intact habitat (P), protected degraded habitat (Pd), and protected managed habitat (Pm).

For the purposes of modelling simplicity we consolidate these into three land use states and define their overall contribution to biodiversity values (Fig. 1a): Converted habitat for multiple use (C) (e.g. housing, agriculture, intensive monoculture forestry) which has low to zero biodiversity value; Modified habitat (M) is at least partially converted or modified for shared land uses, but retains some of its native species and original or new ecosystem functions, including production-based ecosystem services (e.g. grassy strips within cereal crops or parks within cities – these captured the degraded states within Kuempel et al., 2020); Intact habitat (I) is not converted or degraded by other environmental threats, and thus maintains its native species and ecosystem functions and may be formally protected or not (states P, and U within Kuempel et al.). Overall, our model assumes that the contribution to biodiversity is greatest for intact habitat, followed by modified habitat (dependent on species and their preference for spared or shared

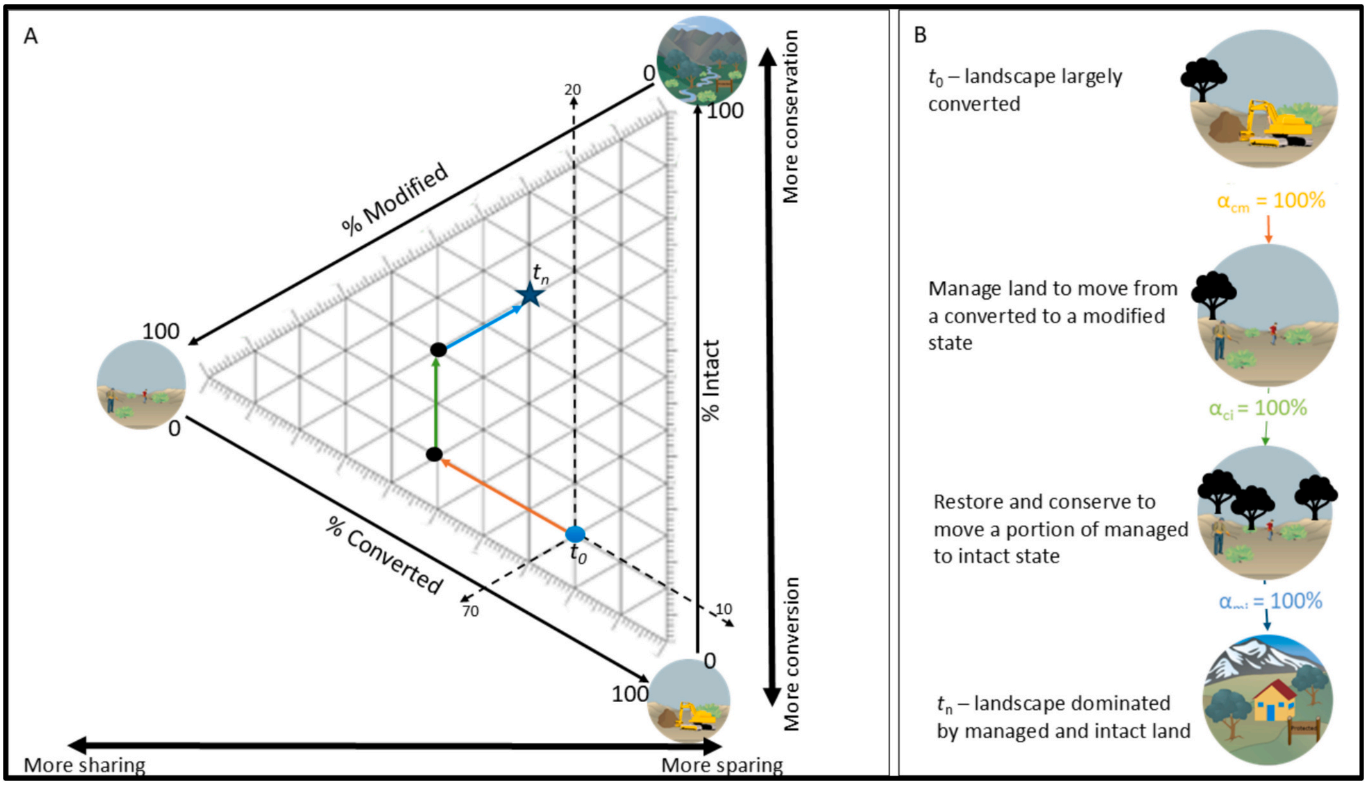

Fig. 1. A) Visual representation of the framework and complex decision landscape and B) Hypothetical decision path a manager can take to move towards a desired future state. To move from the current state at time t_0 (20% modified, 70% converted and 10% intact) towards a desired future landscape at t_n (30% modified, 20% converted and 50% intact; illustrated by the star), a manager can choose from a variety of strategies depending on the planning horizon and preferred actions. The parameters $\propto_{ci}$, $\propto_{mi}$ and $\propto_{cm}$, are the percentage of the total budget spent on the three conservation interventions (intensive restoration, moderate restoration, and partial restoration respectively).

landscapes; Wright et al., 2012). Conversely, we consider that the greatest direct contribution to human needs is in the converted habitat followed by modified habitat.

Depending on the managers' objectives for a landscape, and given the relative contributions of different habitats (I, M and C) to biodiversity outcomes and production values, management actions are needed to shift from the current state, defined by the proportion of each habitat type, to a different desired one. This requires understanding the relative rates of loss of habitat through active conversion (for production and from other threatening processes), and the conservation actions that can be implemented to address these threats. Here, we present a simplified model where habitat loss stems from two processes: active conversion which moves both intact and modified land towards converted land, and habitat modification, which moves intact land towards a modified habitat. Management actions such as intensive restoration moves converted habitat towards an intact state, moderate restoration moves modified habitat towards an intact state, and partial restoration moves converted habitat towards a modified state. There are many on-the-ground actions or policies that can achieve intensive, moderate or partial restoration, including stopping land degradation and active revegetation. The difference between the three types of actions is linked to the current and desired states of the system, rather than effort directly. For example, partial restoration in our framework may involve effort considered intensive (in terms of time and money) but still leave the system in a state considered Modified; from a conservation point of view, here, the restoration is partial because the land is not Intact after investment.

The model is described by the following set of differential eqs. (1–3) where δ_{im} is the rate of habitat modification from intact to modified, δ_{ic} the rate of active conversion from intact to converted, and δ_{mc} the rate of active conversion from modified to converted. The parameters $\propto_{ci}$, $\propto_{mi}$ and $\propto_{cm}$, are the percentage of the total budget (B) spent on the three conservation interventions (intensive restoration, moderate restoration, and partial restoration respectively), such that $\propto_{ci} + \propto_{mi} + \propto_{cm} = 100\%$. Each conservation action i has a different associated cost per unit area ($c_{ci}, c_{mi}$and c_{cm}). For example, eq. 1 describes changes to intact habitat I through 1) area loss to modified and converted states at rates δ_{im} and δ_{ic} respectively and 2) area gain from modified and converted states at rates $\frac{\propto_{mi}}{c_{mi}}$ and $\frac{\propto_{ci}}{c_{ci}}$, respectively, given total budget B.

$$\frac{dI}{dt} = -\delta_{im}I - \delta_{ic}I + \left(\frac{\propto_{mi} \times B}{c_{mi}}\right) + \left(\frac{\propto_{ci} \times B}{c_{ci}}\right), \tag{1}$$

$$\frac{dM}{dt} = -\delta_{mc}M + \delta_{im}I + \left(\frac{\propto_{cm} \times B}{c_{cm}}\right) - \left(\frac{\propto_{mi} \times B}{c_{mi}}\right), \tag{2}$$

$$\frac{dC}{dt} = \delta_{ic}I + \delta_{im}M - \left(\frac{\propto_{cm} \times B}{c_{cm}}\right) - \left(\frac{\propto_{ci} \times B}{c_{ci}}\right) \tag{3}$$

While this model is designed for a system with both modified (M) and converted (C) habitat present, it is also applicable to cases where either C = 0 or M = 0. In that case, degradation from intact (I) to C or M is still possible, however, investment in some of the three conservation interventions is not possible. If there is no converted area in the system, then $\propto_{ci}$ (intensive restoration) and $\propto_{cm}$ (partial restoration) are set to 0 (Supplementary text S1). If there is no modified area in the system, then $\propto_{ci}$ (intensive restoration) is set to 0 (Supplementary text S2).

4. Theoretical application of the framework

We first illustrate our framework and how the system model can inform complex multi time step management decisions with a visual representation of the decision space (Fig. 1A) and a hypothetical example (Fig. 1B). Imagine the current state of the system at time t_0 consists of 20% modified habitat, 70% converted habitat, and 10% intact habitat. The desired landscape consists of 30% modified habitat, 20% converted habitat and 50% intact habitat (at t_n after n years). There are many pathways a manager may choose to achieve the ultimate desired landscape, and the optimal action at a given time step is dependent on the planning horizon, objective, budget and costs of actions, and the benefit function associated with the state of the system. One approach could be to optimize investments over a much longer planning horizon (e.g. several years to several decades into the future) to fully realize the desired state using an optimization method by investing in one action at a time (Fig. 1B). In this case a manager would have to select a desired future state and time frame over which to reach this system state (indicated by a star in Fig. 1A) and the framework presented here could then be used to identify sequential investments for actions, for example converting C to M through active management, then, C to I through active restoration, and finally M to I through protection and management (Fig. 1B).

Visualizing the potential outcomes and available options for sequential management actions can be challenging. We therefore demonstrate a use case of our model by applying it to three empirical case studies with data available to estimate the relevant parameters. For each case study we infer management objectives or goals based on literature and use these to identify management actions a decision maker must choose between to deliver on the objectives. We then generate a complete solution space with our system model to explore how the potential management actions may be applied and the relative costs and benefits of these. This is an example of the simple decision support use case of the framework.

5. Case studies

We further illustrate our proposed model system framework using three case studies from different landscape types (urban, forestry, agriculture), each with multiple objectives (Table 1, Fig. S1). For each case study, we use the system model framework to calculate change in amount of Intact, Modified and Converted land given all possible investment combinations into the management actions that address the landowner's multiple objectives. We also look at the effect of overall budget in achieving objectives running scenarios where the costs of the different management actions are all equal ($c_{ci} = c_{mi} = c_{cm}$) but the overall budget is small, medium, and large relative to the cost of management. Our case studies demonstrate how the system model can be used to visualize the complete decision space over multiple budgets. Such visualisations can be used as decision support tools to enable land managers or policy makers to consider pathways in actions, and needed budgets, to move systems towards a desired end state.

Table 1
Value of model parameters for the three case studies. All costs (c_{ci}, c_{mi} and c_{cm}) were considered to be equal, and we ran the model with three relative budget sizes: small, medium, and large.

Parameters	Urban: Brisbane, Australia	Forestry: Borneo, Indonesia	Agriculture: Darling Downs, Australia
Intact initial (% of total area)	30	44	5
Modified initial (% of total area)	20	20	20
Converted initial (% of total area)	50	36	75
δ_{ic}	0	0.8	7.5
δ_{mc}	0.6	0.8	7.5
δ_{im}	0	0.3	0
Other constraints	$\propto_{ci} = 0$	–	–

6. Urban case study: Brisbane, Australia

Urban areas are the most human modified ecosystems on the planet and are expanding rapidly (Seto et al., 2011). Cities are often built on previously highly productive ecosystems with rich biodiversity (Imhoff et al., 2004). Consequently, urbanisation is considered a highly threatening process for biodiversity and food production, and given the speed and extent of urbanisation, reconciling biodiversity with urban development could not be more imperative. The land sparing versus land sharing framework has been proposed as a mechanism to try to address this challenge (Lin and Fuller, 2013). Land sharing in cities consist of low-density housing with small green spaces such as small parks and private gardens but lack large parks or reserves. Land sparing in cities consist of high density built-up areas in a smaller area allowing large green spaces in the form of large contiguous parks or reserves to be set aside for nature, for example in the heart of London or New York (Lin and Fuller, 2013; Stott et al., 2015), or forest National Parks such as those found in Sydney, Australia.

An urban landscape can broadly be divided into three states: 1) reserves, largely made up of native vegetation that is primarily for conservation and nature-based human amenity outcomes (intact state), 2) small parks or unallocated land (i.e. not houses, industry or transport but urban greenspace used for a wide variety of human cantered purposes not primarily nature) (modified state), and 3) houses and other infrastructure, i.e. built-up area with no provisions for nature. A typical overarching objective for city planners is to optimize housing and amenities while still provisioning green spaces that benefit both humans and biodiversity.

We use Brisbane, in the subtropical region of Queensland, Australia, as an example to illustrate the use of the framework for urban planners to maximise biodiversity while accommodating the increasing housing demand and human needs. Brisbane's new city plan aims to restore 40% of the city area to natural habitat by 2026 (Brisbane City Council, 2014). However, it is also at the centre of the fastest growing regions in Australia with an inner city predicted population to grow by c.28% by 2031 (Brisbane City Council, 2012). Consequently, it is estimated that the city will need approximately 156,000 additional dwellings by 2031.

6.1. Objectives

The overall objectives of urban planners for Brisbane city are to: 1) maximise the quality and quantity of housing to meet the upcoming demands within the budget available and without removing any intact habitat, 2) provide access to parks and informal open space for people (e.g. green space within 400 m walk or five minute drive for inner city residents; Brisbane City Council, 2012), and 3) retain a certain amount of biodiversity and examples of the original ecosystems for cultural reasons and to avoid/minimize local extinctions (Brisbane City Council, 2017). Strategic investment into management and conservation actions can contribute towards achieving these objectives directly and indirectly.

6.2. Actions

In order to achieve the objectives of increasing housing, amenities and revenue stream to accommodate the rising population and requirement for 156,000 additional dwelling while restoring 40% of Brisbane city area to natural habitat, city planners could consider two potential actions, alone or together. First, modified management to increase the area of managed parkland and green space by replacing low rise suburbs with high rise dwelling and more parkland (restoring converted into modified land by investing into $\propto_{cm}$). This may also increase with amount of housing available without altering the amount of habitat in each state. Second, land management to increase the amount of native vegetation to achieve the 40% natural habitat goal by buying and revegetating parkland and bushland with native species, and partnering with residents to restore privately owned bushland (restoring modified into intact by investing into $\propto_{mi}$).

6.3. Costs and constraints

Meeting the infrastructure demand of the growing population while achieving the 40% natural habitat goal will require innovative development plans including smaller apartments, high rises, and use of converted but empty sites. Determining the optimum development plan is further complicated by the constraints given to each action and budget limitations and will therefore involve trade-offs that need to be carefully assessed in terms of costs. A further constraint to the model for this case study is that reserve land should not be developed (intact land cannot be converted) and it is unlikely that intensively used land will be returned to reserve (converted land cannot be restored to intact).

6.4. Using the system model

Based on the aims and objectives of the Brisbane City Council (Brisbane City Council, 2012), we estimated starting values for the model (Table 1), and set investment into active restoration from converted to intact ($\propto_{ci}$) to 0%. There were three hypothetical pathways from the initial starting point that a manager could invest their efforts in order to achieve their objectives (Fig. S1a). The first pathway was to restore modified habitat to intact habitat. The second pathway was to increase the intensity of dwellings in an area to allow for a greater area of parkland (converted to modified). The third pathway was a mix of the two actions.

6.5. Results

With only two actions available to managers, regardless of the budget size, the amount of modified land only increases (purple shading in Fig. 2) when the majority of financial investment goes to partial restoration ($\propto_{cm}$, middle top – bottom panels, Fig. 2); if more than 50% of the budget is allocated to moderate restoration then modified land decreases ($\propto_{mi}$, yellow sharing in Fig. 2). Conversely, the amount of intact land always increases (by design of the actions implemented), but it does so to a greater extent when the majority of investment goes into moderate restoration (left top – bottom panels, Fig. 2).

7. Forestry case study: Borneo, Indonesia

Deforestation and forest degradation are well known drivers of biodiversity loss globally. Timber harvesting including clear-felling and selective logging, plantations, fire, and fragmentation can all negatively affect forest biodiversity resulting in localised extinctions and changes in community composition (Edwards et al., 2014; Meijaard et al., 2005). Forest managers have a challenge to reduce threats to biodiversity and limit carbon emissions from forest degradation while maintaining long term timber supplies and economic viability (Putz et al., 2012). Under the land sparing versus land sharing framework forests can be intensively logged within part of the concession while leaving the rest of the area unharvested (land sparing). Alternatively the forest can be harvested at low intensity across the whole concession (land sharing) (Edwards et al., 2014).

We use Borneo, Indonesia, as the case study as it has lost forest cover

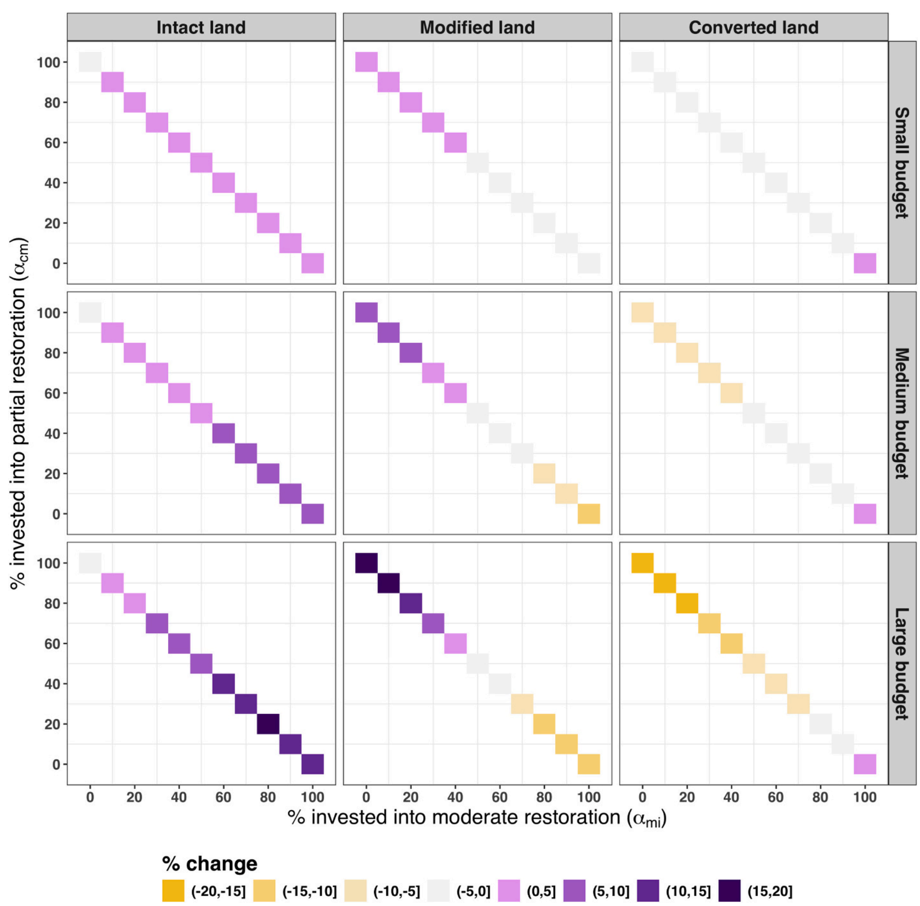

Fig. 2. Direction (positive in purple, negative in yellow) and relative intensity of change in the amount of intact (I), converted (C), modified (M) land in Brisbane over one time step (e.g. one year) given investment into partial ($\propto_{cm}$) and moderate ($\propto_{mi}$) restoration, when the relative budget is small, medium or large. Here the investment into intensive restoration is 0%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

at almost double the rate of the rest of the world's humid tropical forests (Achard et al., 2002). Consequently, approximately 34% of old growth forest has been converted and cleared between 1973 and 2015 (Gaveau et al., 2016). Protecting forests from conversion to plantations, fire and illegal logging is crucial to reducing deforestation rate in Borneo.

7.1. Objectives

Forest managers have a number of objectives to meet in relation to increasing the amount of modified and/or intact habitat: 1) converted habitats become plantations for economic benefits, 2) carbon storage and 3) biodiversity conservation. The latter two objectives are relatively new within forest management but are gaining recognition for the benefits, including economic, both directly and indirectly (Bekessy and Wintle, 2008; Wells et al., 2013).

7.2. Actions

In order to meet these objectives, forest managers can: 1) do partial restoration and establish plantations on previously converted sites and/or plant fast growing timber trees on previously converted sites (restoring converted into modified by investing in $\propto_{cm}$, Fig. S1b) or 2), or actively restore primary forest and protect them from being cleared or modified (restoring converted or modified into intact by investing in $\propto_{ci}$ and/or $\propto_{mi}$; Fig. S1b).

7.3. Costs and constraints

Retaining natural forest and minimizing their conversion to other uses including plantations is priority. However, plantations bring high short term economic benefits to the country and are a substantial component of the country's economy (Fisher et al., 2011). Political decentralisation and instability, and lack of clear laws governing forest lands constrain the ability to protect and preserve old growth forest (Gaveau et al., 2016).

7.4. Using the system model

We estimated model parameters based on Gaveau et al. (2016) (Table 1). Under the current practises on the island, intact habitat is constantly being modified and converted. In order to provide the economic gains of plantations and high-quality timber while reducing the amount of converted habitat, the amount of modified habitat will increase.

7.5. Results

For this case study, if the only aim was to increase timber production while reducing converted habitat (i.e. to increase modified habitat, middle top – bottom panels in Fig. 3) then investment would have to be in partial restoration ($\propto_{cm}$) with minimum investment in intensive restoration or moderate restoration. In addition, all combinations of investment in management actions lead to positive outcome for biodiversity by increasing the amount of intact habitat (left top – bottom panels in Fig. 3). However, Intact land shows the greatest gain when the majority of investment is in either moderate or intensive restoration.

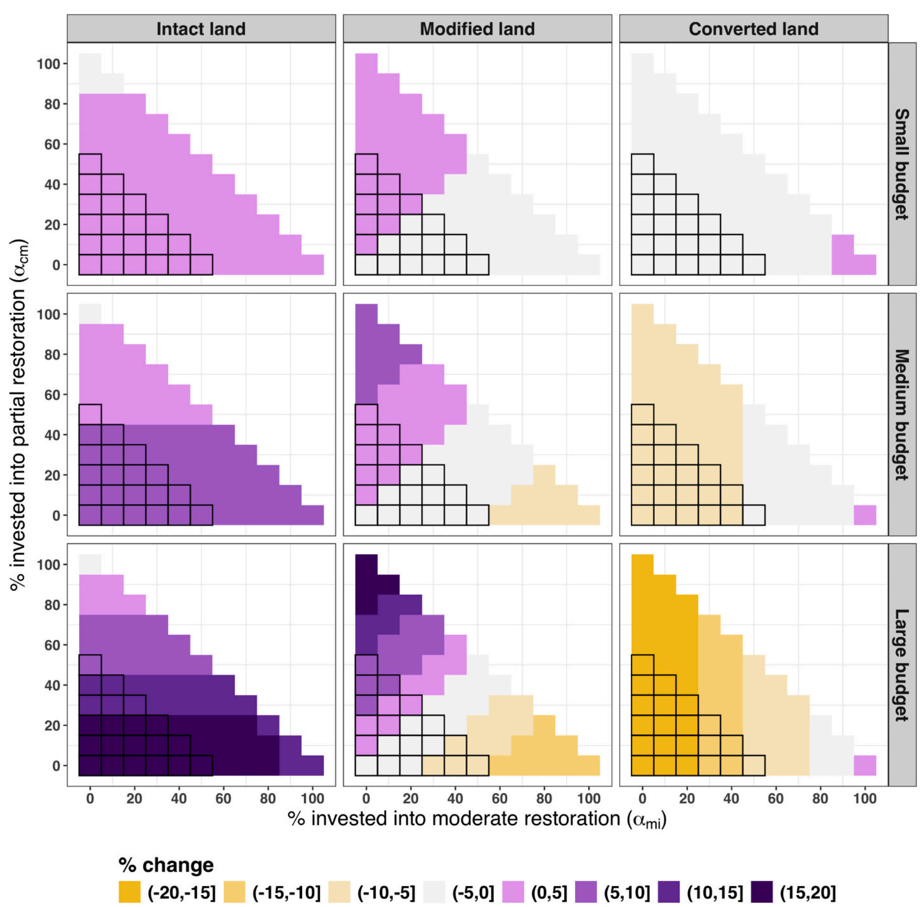

Fig. 3. Direction and relative intensity of change in the amount of intact (I), converted (C), modified (M) land in Borneo over one time step (e.g. one year) given investment into partial ($\propto_{cm}$), moderate ($\propto_{mi}$) and intensive ($\propto_{ci}$) restoration, when the relative budget is small, medium or large. Cells with a black border indicate where the majority of investment goes to intensive ($\propto_{ci}$) restoration.

8. Agriculture case study: Darling downs, Australia

Loss of biodiversity and future productivity in agro ecosystems is a major global concern. The majority of agriculture is dependent upon biodiversity, for example insects for pollination and natural pest control, which underpins a wide variety of ecological goods and services (Power, 2010). Even high intensity cropping systems rely greatly on supporting and regulating ecological services and thus consideration of both production and biodiversity is essential in productive agricultural systems (Bommarco et al., 2013).

Within agricultural landscapes, land use can be divided into three main types: arable land (converted), semi-natural areas such as grasslands and forests (modified), and occasionally nature reserves or protected areas (intact), although the latter areas are rare in agricultural setting. Semi-natural areas can range from small patches of unused vegetation such a grassy field boundaries or banks of water courses to unmanaged woody patches and set-aside fields, and the proportion of these land use types vary in different farm types.

We use the Darling Downs, situated 200 km west of Brisbane, Queensland, Australia as a case study. The area is known for its diverse productive agriculture, due primarily to extensive vertisol soils and humid sub-tropical to semi-arid tropical climate. The area is farmed primarily for summer and winter crops including cotton, sorghum, legumes, wheat and barley.

8.1. Objectives

The main objectives of the majority of farmers are to: 1) maximise their yield and thus income (i.e. increase production) and 2) minimize their risk from pest infestation, weeds, fire or development of insecticide resistance (Jellinek et al., 2013) (i.e. increase modified or intact habitat). In addition, a third objective of maintaining biodiversity (i.e. increase modified or intact habitat) is of importance to a small but increasing number of farmers who see themselves as stewards of biodiversity and ecosystem services (Greiner, 2015; Januchowski-Hartley et al., 2012) and/or understand that protecting and maintaining native vegetation will also provide private benefits (Januchowski-Hartley et al., 2012). However, in relation to the latter objective, farmers are often constrained financially. In some countries subsidies exist for certain interventions to benefit biodiversity (e.g. agri-environmental schemes in EU, US Conservation Reserve Program, Victorian Bush Tender Program) but these are voluntary and by no means global (Claassen et al., 2008; Kleijn and Sutherland, 2003; Stoneham et al., 2003). In addition, a lack of information and uncertainty of management actions that benefit biodiversity and production (e.g. Page and Bellotti, 2015) discourage farmers from engaging in biodiversity friendly practises.

8.2. Actions

In order to meet these objectives while preventing any further increase in converted habitat the main actions that farmers can take are: 1) restore converted habitat to accommodate both agriculture and biodiversity to increase yield and farm income while minimizing the risk to biodiversity and/or manage habitat for natural pest control on their land (restore converted into modified habitat by investing in $\propto_{cm}$; Fig. S1c) or 2) take land out of production and revegetate, or improve non-productive land (restoring converted to modified, converted to intact ($\propto_{ci}$) and/or modified to intact ($\propto_{mi}$) by investing into any of these actions; Fig. S1c). This later action is rare in productive agriculture areas although agri-environmental schemes and similar programs encourage farmers to revegetate certain areas on the farm in return for a financial reward.

8.3. Costs and constraints

Generally, farms are privately owned and managed, and farmer's budgets are often the primary constraint on the actions taken. Financial gain and risk reduction are important for farmers. In order for farmers to voluntarily revegetate parts of their farm there generally need to be both an understanding the indirect benefits biodiversity bring to production (Bommarco et al., 2013) as well as a direct financial subsidy for undertaking such action; these are available in some countries through certain agri-environment schemes.

8.4. Using the system model

The model parameters (Table 1) for this case study were estimated using GIS data. The average amount of intact (mainly riparian vegetation), modified (disturbed semi-natural area) and converted (mainly crop) areas within a 1km^2 area (average farm management size) was calculated from 24 landscapes.

8.5. Results

We found that positive gains can be made to the amount of intact habitat for all budget sizes for all combinations of management actions when investment in partial restoration is $\leq$80% (left top – bottom panels; Fig. 4). Overall, the amount of additional Intact land that can be achieved, however, is lower than in the Forestry case study (Fig. 3) as a result of the larger conversion rates to Converted land (Table 1).

9. Discussion

Creating a landscape which meets multiple objectives, such as conservation of biodiversity, production of food and fibre or provision of urban amenity is not an easy task. Navigating these multiple objectives and trade-offs requires a nuanced approach to decision making that accounts for multiple pathways towards desired system states, and ultimately supports decision makers in implementing incremental decisions through time to change the system (Álvarez-Romero et al., 2015). The traditional land sparing versus land sharing framework focuses on selecting the landscape design to maximise the species richness or abundance of specific species or communities of conservation concern (Green et al., 2005; Phalan et al., 2011). While this framework presents a way of identifying the desired final landscape design that delivers on multiple objectives, it does not tell us what path to take between the desired and current landscape, especially when it is not linear. The focus of the proposed system model and framework is to support decision makers in identifying management pathways for incremental changes to move the system towards a more desirable state, based upon multiple objectives at the appropriate spatial scale.

Our proposed approach is to use the framework and system model to develop an understanding of the entire solution space to then establish incremental movement towards a landscape that meets the goals. In doing so it provides a transparent decision framework for adaptive planning and decision making. Such a decision framework must include the current state of the landscape and background rates of change, a clear set of objectives, associated actions with their costs, and a total budget (Carwardine et al., 2008). Pairing this approach with a generalised system model, we illustrate the potential landscape changes that can occur through different management actions in three example landscapes. Our model identifies possible pathways to follow to ensure the appropriate proportion of the landscape is allocated to each state to deliver based on relevant actions that will deliver on objectives. However, this does not tell managers where or when to act. To best support decision making, our proposed system model should ideally be integrated into an optimisation (through stochastic dynamic planning embedded within structured decision making Martin et al., 2009) and/or spatial prioritisation algorithm (e.g., Marxan embedded within

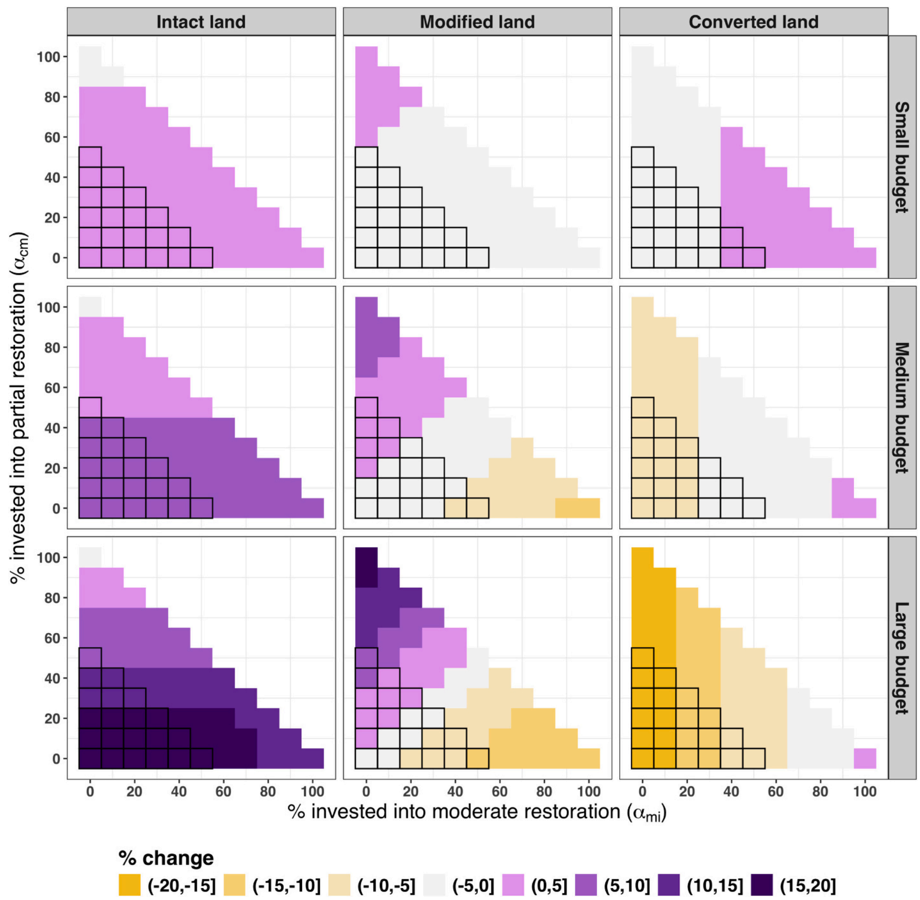

Fig. 4. Direction and relative intensity of change in the amount of intact (I), converted (C), modified (M) land in the Darling Downs over one time step (e.g. one year) given investment into partial ($\propto_{cm}$), moderate ($\propto_{mi}$) and intensive ($\propto_{ci}$) restoration, when the relative budget is small, medium or large. Cells with a black border indicate where the majority of investment goes to intensive ($\propto_{ci}$) restoration.

systematic conservation planning Giakoumi et al., 2025) to provide guidance around the spatial placement of actions to define the desired landscape and then determine the best locations (Martinez-Harms et al., 2021; Venter et al., 2009; Wilson et al., 2010). Pairing the proposed system model with an optimisation framework could also provide time-dependent recommendations for specific actions. This will allow planners and managers to plan for future targets and circumstances on the land.

The case studies demonstrate how our approach can be readily applied to a range of landscapes to inform decision making. This approach can be used by land managers or policy makers to predict the effect of different actions on the overall landscape and determine the optimum actions required in order to achieve their objectives within a given budget, and realistic timeframes. Each of the case studies illustrates that varying the investment in different conservation actions can allow the different objectives of the landowner to be met within the available budget. This allows managers to predetermine outcomes from different actions costing different amounts, which is a valuable tool for both conservation and production.

A key benefit of our high-level model is that it is not spatially restricted and can be used in any landscape and at any spatial scale. Each of our case studies varies in spatial scale, current landscape compositions and rate of change. A key consideration for decision makers when they apply our system model is to define a meaningful spatial scale for the approach. Additionally, it will be important to define the scale at which actions are taken to make sure they match the objective; this will avoid potential issues with an area may be classified as land sparing at the farm level but land sharing at the regional level (Fischer et al., 2014).

Two parameters of our system model – rate of habitat conversion and cost of action – consistently drove the results, highlighting the importance of considering them in decision making. This is consistent with studies that have found optimisations seeking to minimize loss outperform those seeking to maximise gain(Visconti et al., 2010). Within our case studies, the current rate of habitat conversion across the landscape largely affects the outcome of conservation management emphasising the importance of including the dynamic nature of the landscape rather than a static snapshot in time. Our results consistently show that when the rate of conversion is high it takes considerably more action, and hence cost, to achieve positive conservation gains in terms of more intact habitat. Commonly the current management and rate of habitat loss is not considered in conservation management plans meaning that the cost of obtaining the desired landscape is often considerably higher than planned and thus unattainable within the available budget (Adams, 2024).

Similar to rates of loss, the cost of actions is often ignored or poorly estimated in conservation prioritisations, leading to inefficient decisions and expensive mistakes (Adams, 2024; Armsworth, 2014). As would be expected, changes in the cost of management actions can largely affect their outcomes with greater benefits for conservation being possible when the cost of actions are low (as shown in Supplementary figs. 1–3 where the increase in state I is greatest when the cost of actions are low). Failure to include the costs can result in idealistic actions being suggested that may not be financially viable. Although, in our case studies, we have made the cost of all actions the same for simplicity, different actions are likely to accrue different costs, and these can be factored into the decision-making process.

This research is directly applicable to land management policy. One of the criticisms of linking science outcomes to policy is that scientists 'fail' to ask policy relevant questions and provide an approach that is timely and consistent. The framework proposed overcomes some of these criticisms; it is generalizable, transparent and flexible. The current state of landscapes (as the starting point for the case studies) are often the result of a policy already in place. Therefore, this framework can be used as a tool where policies can be treated as hypotheses that can illustrate to decision makers the costs and trade-offs (Perrings et al., 2011; Thompson et al., 2011).

Our spatially independent multi-state landscape model provides a more realistic and feasible decision framework to aid land managers in meeting both conservation and production targets. The approach can be used globally in any landscape type so long as the objectives, actions and cost of those actions are explicitly known. It can be coupled to complex benefit functions that incorporate variable benefits associated with different system states, for example food production on modified or converted lands, and biodiversity on modified or intact lands. Our model can also be made or less complex by varying costs of actions and rates of degradation. This allows landscapes to be managed accordingly to meet different objectives within the available budget. This provides for more attainable and acceptable decisions to be made over the management of the landscape.

CRediT authorship contribution statement

Alienor L.M. Chauvenet: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Anna R. Renwick:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Conceptualization. **Hugh P. Possingham:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Vanessa M. Adams:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jennifer McGowan:** Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Vesna Gagić:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Nancy A. Schellhorn:** Writing – original draft, Validation, Supervision, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Hugh Possingham reports financial support was provided by Australian Research Council. Anna Renwick reports financial support was provided by Commonwealth Scientific and Industrial Research Organisation. The other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2026.111717.

Data availability

Data will be made available on request.

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